The LHCb vertex locator: present and future

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LHCb is a forward-angle spectrometer, dedicated to the study of b-hadron physics, which is presently under construction at the Large Hadron Collider (LHC) at CERN. The main task of the Vertex Locator (VELO) is to reconstruct primary and secondary vertices. It consists of two retractable detector halves with 21 silicon micro-strip tracking modules mounted in a vacuum vessel as shown in Figure 1.

The silicon detectors are operated in a secondary vacuum which is separated from the primary (beam) vacuum by a so called RF-box constructed from 300 μm thick Aluminium foils. This box also shields the sensors from the strong wakefields generated by the intense LHC beams. The shape of the foil is optimized to minimize the amount of material in order to obtain the best possible coordinate resolution, while at the same time it accommodates for a small overlap of the sensors from the two detector halves.

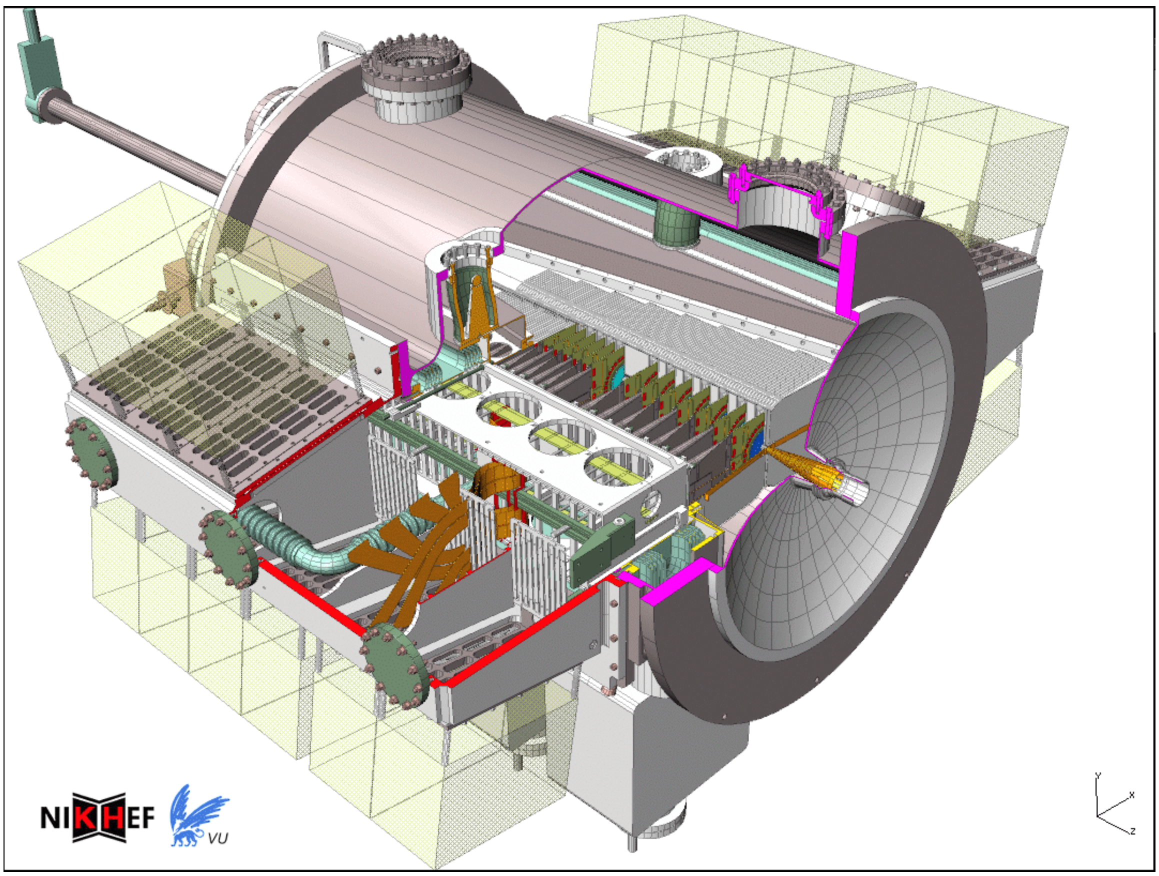

Figure 1. Overview of the LHCb vertex locator (VELO). The silicon micro-strip tracking modules are mounted on two retractable detectors halves.

Silicon module

A silicon module is composed of two half-discs of 300 μm thickness with R and Φ micro-strip geometry (see Figure 2). This R-Φ geometry allows for fast R-Z track reconstruction in 2D in the level-1 trigger algorithms. The strip pitch varies from 40 to 102 μm and from 36 to 97 μm, for an R and Φ sensor, respectively. The first sensitive element of the sensor is positioned at 8.2 mm from the colliding beams.

Figure 2. Picture of two complete silicon modules. Each module consists of an R and an Φ measuring sensor which are read out by 16 Beetle chips.

The harsh non-uniform radiation environment has led to the choice of diffusion oxygenated float zone sensors with n_+ strips in n-bulk and p_+ ohmic contacts on the back plane. Each sensor has 2048 strips which are routed via a second metal layer on the sensor to 16 analog Beetle1.5 chips. These chips, which are especially developed in a radiation tolerant 0.25 μm technology, have an integrating preamplifier followed by a semi-Gaussian shaper with a peaking time in the order of 20 ns. The shaped signals are sampled at the 40 MHz LHC bunch crossing frequency and subsequently stored in an analog pipeline. The characteristics of the Beetle front-end can be fine tuned via DAC settings. Upon receipt of a trigger, the analog values are retrieved from the pipeline and sequentially sent out to the off-detector digitizing electronics. The Beetle chip has a 16 deep derandomizing buffer which facilitates a sustained level-0 trigger rate of 1.1 MHz. The Beetle chip has been shown to be operational up to 130 Mrad and shows negligible analog performance loss up to 40 Mrad.

The electronic components are mounted on polyimide (kapton) circuits which have excellent radiation hardness and vacuum properties. The kapton circuits are glued back to back on a carbon fibre substrate with a TPG (Thermalised Pyrolitic Graphite) core for heat conduction. Cooling of the sensor and the front-end chips is realized by a two-phase $C0_2$ cooling system. A cooling liquid temperature of -35 ºC results in a silicon temperature of about -5 ºC.

In addition to the 21 R-Φ stations four stations with only R-sensors, located in the upstream hemisphere, form the Pile-up system. It features prompt digital readout and will veto bunch crossings with more than one interaction by means of dedicated vertex finding algorithms implemented in FPGAs. A decision on the number of vertices is delivered every bunch crossing and is used to reduce the level-0 trigger rate to the maximum of 1.1 MHz dictated by the readout of the entire LHCb detector.

Status

In May 2006 the VELO vacuum vessel including, its PLCs for the vacuum control and the movement control of the two detector halves, was installed at the LHCb interaction point. Currently, tests are ongoing to qualify the system for operation with the LHC vacuum.
The first mechanical detector half with the cooling tubes for the 21+2 stations has been tested and transported to CERN. The production of the silicon modules has ramped up to full speed and the first physics grade modules are being delivered to CERN at this very moment. Many parts of the modules are already produced, qualified, and are available in large quantities for assembly into complete modules. Hence the production rate of modules is expected to be more than two per week for the coming months.

Beamtest results

In 2004 the final layout of the silicon sensor (version PR04) has been tested together with various versions of the Beetle chip (version 1.3, 1.4 and 1.5). The most important parameters of the 200 μm thick sensor and readout chip combination are the Signal to Noise ratio (S/N), the peaking time, the remainder of the shaped pulse 25 ns after the peaktime. The latter parameter, called overspill, should be low in order to reduce the number of ghost hits. It was found that with Beetle version 1.5 a S/N of more than 16 could be obtained, while at the same time the peaking time is about 20 ns and the overspill ranges from 19 to 24 % for short and long strips, respectively (see Figure 3).

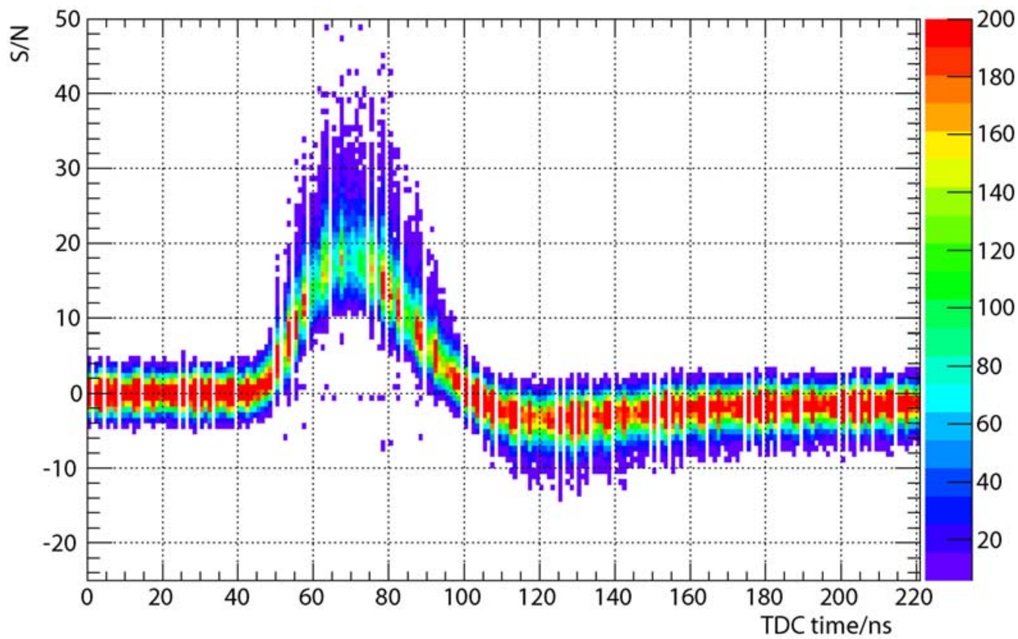

Figure 3. Pulseshape of a Beetle1.5 chip bonded to a 200 μm silicon sensor. The (most probable) signal to noise ratio is 16, the peaking time is about 20 ns and the spillover is 20%.

These parameters fulfill the requirements of the LHCb vertex detector. Note that the quoted signal to noise ratio is obtained with a 200 μm thick sensor while the VELO will be equipped with 300 μm sensors giving an extra margin in the S/N. The VELO will be operated in an intense radiation environment and hence, the extra silicon thickness means an extended lifetime of the silicon sensors at the cost of an increase in multiple scattering.
The first three fully equipped double sided modules have been tested in a beamtest in August 2006. A full readout chain was used which consisted of the final version of all electronics boards that will be used in the experiment. Data has been acquired for numerous settings of the detector and its electronics. The analysis of this data is ongoing.
It is envisaged to go once more to a testbeam before the installation of the active part of the detector in the experiment in early 2007. The aim is to test a complete detector half with 21 R-Φ stations.

Upgrade

Under nominal LHCb running conditions the lifetime of the VELO detector is expected to amount to 3 years. Note that the during the first year of LHC running, which is expected to begin in autumn 2007, the luminosity will be much lower than the nominal value of 2.10^{32} $cm^{-2}s^{-1}$. Hence the replacement of the VELO is not expected before 2011. Because of the limited lifetime, various upgrade scenarios are already under study.
Upgrade scenarios can roughly be divided two categories, technology upgrades and performance upgrades. In the first category new detector technologies like, n in p sensors, Czochralski silicon, 3D silicon and pixel detectors are being explored. The driving force behind a technology upgrade is the need for sensors with increased radiation hardness.
Radiation harder detectors are even more important considering the wish to reduce the distance to the beam from the current 8.2 mm to 5 mm which is the limit set by the LHC machine.
Considering the limiting factors of the VELO performance, the two dominating factors are the, already mentioned, distance to the beam and the limited coordinate resolution due

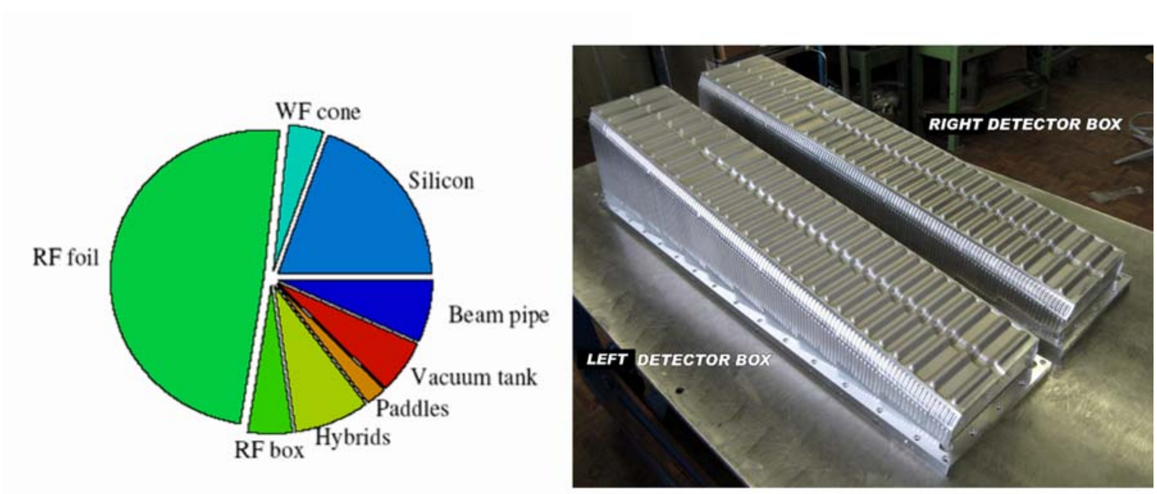

Figure 4. Contribution to the material budget of all materials in the VELO (left). The RF-boxes shown on the right side contribute most.

to multiple scattering. Figure 4 shows the breakdown of all the materials in the VELO in terms of its contribution to the material budget. The two largest contributions to the total material budget of 19% X_0 are the corrugated RF-foil and the silicon sensors.

The thickness of the silicon sensors for the first generation VELO is 300 μm. Using 200 μm sensors poses no problem for the performance as long as the charge collection efficiency is sufficiently high. With the current silicon sensor technology this implies a lifetime in the order of 2 years which is unacceptably low. New sensor developments might push this limit to more than 5 years.

The 300 μm thick Aluminium foil, from which the RF-box is formed, separates the silicon modules from the primary ultra high (beam) vacuum. In addition it shields the modules from the wakefields of the passing hadron beams. Studies are ongoing to reduce the thickness of the foil. Other options like RF shielding by wires are also being considered.